PLASMA OF ELECTRIC ARC DISCHARGE BETWEEN COPPER ELECTRODES IN A GAS FLOW

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Spectroscopy investigations of the thermal multicomponent plasma of the electric arc discharge between copper electrodes in carbon dioxide and argon flows were carried out. The technique of calculation of plasma equilibrium composition is discussed. The influence of hydrodynamic cooling of gas flow on the plasma state is estimated. It was assumed that the thermal dissociation of molecules of working gas play the key role in deviation from local thermodynamic equilibrium (LTE) in plasma.
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1. INTRODUCTION

As well known, a gas shielded arc is often used in electric arc technology. A welding or arc cutting processes is usually realized in argon, carbon dioxide, nitrogen, oxygen and air or mixtures of different gases. From one hand the spatial distribution of plasma parameters are depended from flow rate or kind of surround gas. And from another hand the metal vapour content in arc discharge significantly determine these parameters too. Therefore the investigations of electric arc plasma with metal vapour in different shielding gases are interesting from the viewpoint of industrial applications and studying of basic physical phenomena as well.

2. CALCULATION OF PLASMA EQUILIBRIUM COMPOSITION

It is possible to calculate plasma composition in the assumption of LTE using temperature and electron density as known parameters.

The simplest situation is when we have electric arc discharge in monoatomic gas such as argon. The calculation of the plasma composition in this case can be carried out by solution of the equations of perfect gas, charge neutrality and Saha at a given pressure. For arc discharge between copper electrodes we have to add one more Saha equation due to the presence of copper vapour in the discharge volume and equation of charge neutrality must be improved for copper ion density.

When we consider electric arc discharge in molecular gases or its mixtures, the influence of processes of chemical reactions must be included in the calculation of the plasma composition. The next problem is in determination of the most important chemical reactions.

For example, carbon dioxide can be chosen as plasma working gas. More than ten reactions occur for this molecule and its secondary particles.

In our previous investigation [1] we considered that with increasing temperature molecules of carbon dioxide dissociate in such way:

$$CO_2 \Leftrightarrow C + 2O . \qquad (1)$$

As dissociation energies of molecules O_2 (5.1 eV) and C_2 (6.2 eV) are rather low it was assumed that only atoms and ions of oxygen and carbon would be present in plasma. The ionization potential of molecules CO_2 is rather high (13.79 eV) and the amount of such molecules is insignificant as the dissociation degree of carbon dioxide at temperature value 6000 K equals 0.986 [1]. Consequently, the amount of ions CO_2^+ would be negligible. It was considered that there are following particles in plasma: Cu, Cu^+, C, C^+, O, O^+, CO_2 and electrons.

In this paper to describe chemical reactions in carbon dioxide we took into account next reactions:

$$\begin{aligned} CO_2 &\Leftrightarrow CO + \tfrac{1}{2}O_2 \\ CO &\Leftrightarrow C + O \\ O_2 &\Leftrightarrow 2O \end{aligned} \qquad (2)$$
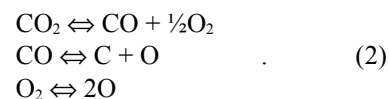
Therefore the calculation of the plasma composition was carried out by solution of the equations of perfect gas (3), charge neutrality (4), Saha (5), Guldberg-Waage (6) and global chemical equilibrium (7) at an atmospheric pressure using temperature and electron density obtained from experimental investigation. The ionization potentials of molecules CO and O_2 are 14.01 eV and 12.08 eV respectively, therefore their presence can be neglected. In such improved calculation we considered that plasma consist from Cu, Cu^+, C, C^+, O, O^+, CO, O_2, CO_2 and electrons.

$$p = k_b T N_{all} , \qquad (3)$$

$$N_e = \sum N_{i^+} , \qquad (4)$$

$$S_i(T, N_e) = \frac{N_e N_{i^+}}{N_i}, i \Rightarrow Cu, C, O , \qquad (5)$$

$$D_{CO_2}(T) = N_{CO} N_O^{1/2} / N_{CO_2} ,$$
$$D_{CO}(T) = N_C N_O / N_{CO} , \qquad (6)$$
$$D_{O_2}(T) = N_O^2 / N_{O_2} ,$$

$$N_O + 2N_{O_2} + N_{O^+} = N_{CO} + 2N_C + 2N_{C^+} . \quad (7)$$

Such approach shows very good agreement with other authors [2] in the range 3000 K < T < 15000 K.

2. EXPERIMENTAL INVESTIGATIONS

The arc was ignited between the end surfaces of the non-cooled electrodes in a working gas flow of 6.45 slpm. The diameter of the rod electrodes was of 6 mm. All experimental investigations were carried out in average cross section of discharge gap of 8 mm at arc currents 3.5 and 30 A.

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Because of the discharge spatial and temporal instability the real-time recording of the spatial spectral line emission was used. A CCD linear image sensor accomplished fast scanning of spatial distributions of radiation intensity [3].

To determine the radial profile of electron density we investigated the shape of spectral line CuI 515.3 nm broadened by the dominating quadratic Stark effect. The measurements were carried out by techniques based on a Fabri-Perot interferometer (FPI) [3].

Unfortunately the width of this spectral line at arc current 3.5 A is practically comparable with instrument function of FPI. Therefore, to extend the measuring range of the electron density we studied the radial distribution of absolute intensity of a spectral line CuI 465.1 nm [3].

The radial temperature profiles $T(r)$ were determined by Boltzmann plot method using CuI spectral lines 465.1, 510.5, 515.3, 521.8 and 578.2 nm. We used spectroscopic data from [4].

3. RESULTS AND DISCUSSIONS

Radial profiles of plasma temperature $T(r)$ and electron density $N_e(r)$ for different experimental modes are shown in Figs. 1-4. These results were used in calculation of plasma compositions (see Figs. 5, 6) by improved set of equations Eq. 3-7.
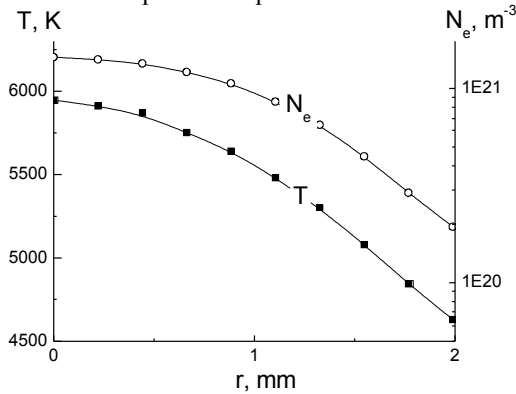

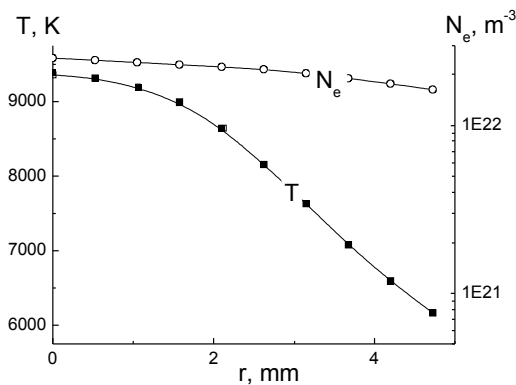*Fig.1. Radial profiles of T and N_e for CO_2 flow at 3.5 A*

Fig.2. Radial profiles of T and N_e for CO_2 flow at 30 A

According to previous calculations [1] the electric discharge plasma in CO_2 flow at arc currents 3.5 and 30 A cannot be in LTE. In our case this conclusion confirmed only at arc current 30A in axial region of discharge (see Fig. 6). The difference at 3.5 A can be explained by analysis of approaches for calculation equilibrium composition. In contrast to [1] we add into consideration CO and O_2 in plasma. As one can see densities of these particles are sufficiently high (see Fig. 5). Therefore, it is necessary to take into consideration CO and O_2 particles for temperatures lower than 6000 K. In the range $6000 < T < 15000$ K simplified technique [1] can be used.
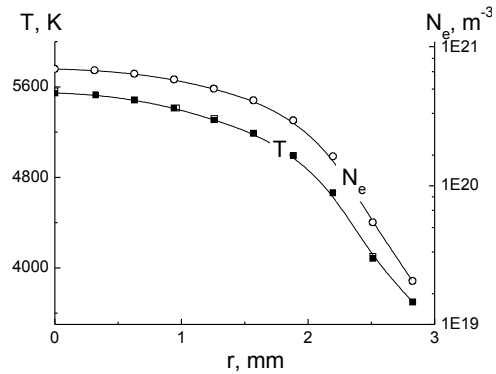

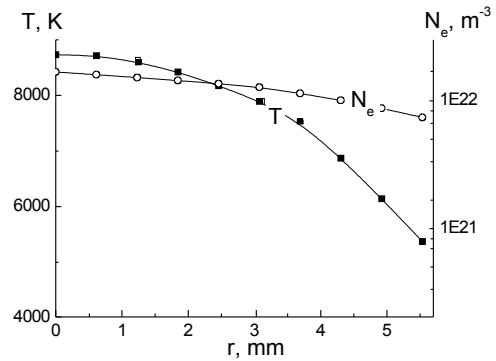*Fig.3. Radial profiles of T and N_e for Ar flow at 3.5 A*

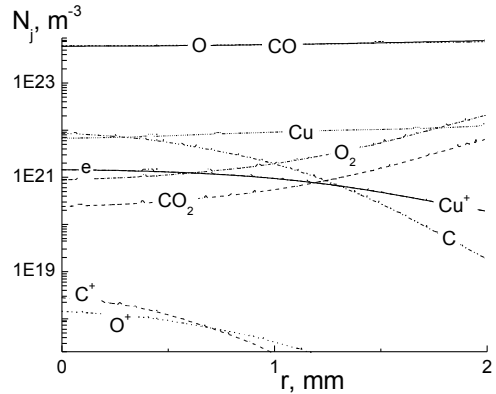*Fig.4. Radial profiles of T and N_e for CO_2 flow at 30 A*

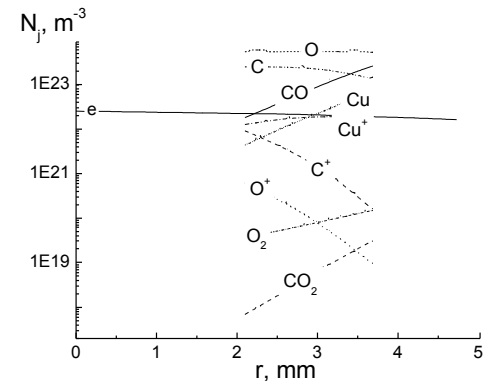*Fig.5. Plasma composition for CO_2 flow at 3.5 A*

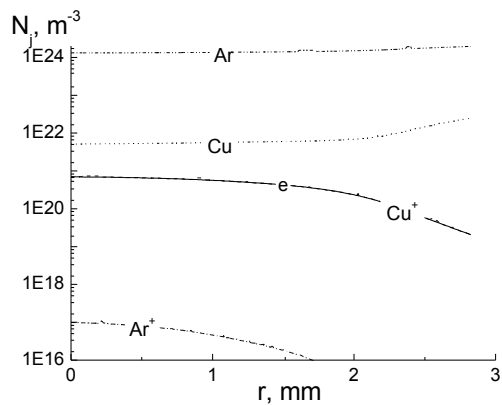*Fig.6. Plasma composition for CO_2 flow at 30 A*

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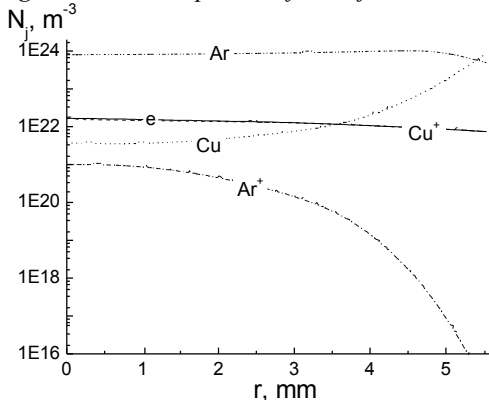*Fig.7. Plasma composition for Ar flow at 3.5 A*

Fig.8. Plasma composition for Ar flow at 30 A

In paper [1] the non-LTE state of CO_2 plasma was explained by the thermal dissociation of molecules of working gas and hydrodynamic cooling of a gas flow. To estimate the influence of such gas cooling we provide similar investigations where argon as working gas was used. It was found (see Figs. 7,8) that this effect have no influence on the deviation from LTE in argon plasma.

Therefore, one can assume that hydrodynamic cooling would not effect on the state of CO_2 plasma at the same conditions as well. By this assumption it is possible to suppose that the thermal dissociation play the key role in deviation from LTE in CO_2 plasma at arc current 30 A.

CONCLUSIONS

The technique of calculation of the CO_2 plasma equilibrium composition was improved. It was shown that in the range of temperatures lower than 6000 K it is necessary to take into account CO and O_2 particles.

It was shown that hydrodynamic cooling does not effect on the deviation from LTE in monoatomic plasma at the flow rate of 6.45 slpm. It is reason to state that this effect has no influence on state of molecule gas plasma too. Therefore, it was assumed that only the thermal dissociation plays the key role in deviation from LTE in CO_2 plasma.

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ПЛАЗМА ЭЛЕКТРОДУГОВОГО РАЗРЯДА МЕЖДУ МЕДНЫМИ ЭЛЕКТРОДАМИ В ПОТОКЕ ГАЗА

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Спектроскопическими методами исследована термическая многокомпонентная плазма электродугового разряда между медными электродами в потоках аргона и углекислого газа. Обсуждается методика расчета равновесного состава плазмы. Оценено влияние гидродинамического охлаждения потоком газа на состояние плазмы. Предполагается, что термическая диссоциация молекул рабочего газа является основным механизмом отклонения от локального термодинамического равновесия в плазме.

ПЛАЗМА ЕЛЕКТРОДУГОВОГО РОЗРЯДУ МІЖ МІДНИМИ ЕЛЕКТРОДАМИ У ПОТОЦІ ГАЗУ

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Спектроскопічними методами досліджено термічну багатокомпонентну плазму електродугового розряду між мідними електродами у потоках аргону та вуглекислого газу. Обговорюється методика розрахунку рівноважного складу плазми. Оцінений вплив гідродинамічного охолодження потоком газу на стан плазми. Припускається, що термічна дисоціація молекул робочого газу є основним механізмом відхилення від локальної термодинамічної рівноваги в плазмі.